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Spacecraft Design Program at the Naval Postgraduate School

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ABSTRACT

This paper presents a review of the spacecraft design program at the Naval Postgraduate School. This program is part of the space systems engineering curriculum. In this curriculum, the students take at least one course for each spacecraft subsystem. The spacecraft design is a three course design sequence. The first course is on spacecraft design tools. The students become familiar with the spacecraft design tools that are used in the final design course. The tools include STK, IDEAS, NASTRAN, and MATLAB/Simulink. They also become familiar with system software such as Aerospace Corporation Corporation Conceptual Design Center tools and spacecraft cost estimation. The second course is on spacecraft system engineering where they review the design aspects of all subsystems, systems engineering, and do an individual design project. In the final capstone course, they do a team spacecraft design project. The spacecraft performance requirements are given by a sponsor. The students have mentors in each subsystem from industry, Aerospace Corporation and government laboratories. The final review is attended by senior spacecraft designers from industry, Aerospace Corporation and government. The Naval Postgraduate School has a Spacecraft Design Center, which is dedicated to these courses. The paper will also present results of a spacecraft design project, Space Based Radar, recently undertaken under this program.

I. INTRODUCTION

Space systems are playing an increasingly critical role in war fighting efforts of the US Department of Defense (DoD). It is critical that military officers are knowledgeable in space systems to perform their tasks properly in requirements, science and technology/research and development, acquisition, and operation. There is currently great emphasis in DoD to educate Space Cadre to perform these tasks. Recently, there has been schedule delays and cost over-run on several space programs. One of the reasons has been attributed to the lack of adequate space systems engineering knowledge from DoD personnel.

The objective of space systems program at the Naval Postgraduate School (NPS) is to educate DoD space cadre personnel to fill each link in the National Security-Space Chain: requirements, science and technology/research and development, acquisition, and operation. A break in this chain will result in failure to deliver national war fighting capabilities. This paper provides an overview of the space systems program at the Naval Postgraduate School with an emphasis on the spacecraft design program.

II. SPACE SYSEMS PROGRAM

The NPS space system program responds to sponsors' Educational Skill Requirements (ESR's), Ref. 1. The program has two curricula: Space System Engineering (SSE) and Space Systems Operations (SSO). Figure 1 shows ESRs for the curricula. The NPS space program is tailored to defense needs. Over 20 years of development work has gone into the curricula, tailoring the coursework and research efforts in support of military space warfare. There are several classified courses on military space systems and 115 NPS faculty are cleared to do classified research. The students are also exposed to military space organizations, defense contractors and national laboratories under a 6 week thesis/work experience. The program is accredited by Western Associations of Schools (WASC) and Accreditation Board of Engineering and Technology (ABET). The program is built upon the expertise and knowledge from the Space Systems Academic Group (SSAG), which is an interdisciplinary association of 20 faculty members representing seven academic departments and academic chair professors. The program has academic chair professors representing NASA, Technical Exploitation of National Capabilities Program (TENCAP), National Reconnaissance office (NRO), Navy, and Space Industry and military faculty including astronauts.

In the SSE, the emphasis is on requirements, science and technology/research and development and acquisition in an operational context. The students get adequate knowledge in all space subsystems/systems integration and hands-on experience in spacecraft design and testing in order to work as a space system engineer in DoD space program offices. The students take at least one course in each spacecraft sub-system and three spacecraft design and integration courses. The course matrix is shown in Figure 2 for the Space Systems Engineering. The course matrix consists of two parts. One part is core courses to meet ESR requirements. The second part consists of specialization courses to meet the MS degree requirements. Based on their BS degrees, students select one of the three degrees: MS Astronautical Engineering, MS Physics, and MS Electrical Engineering. The program is supported by several unique laboratories. Spacecraft Research and Design Center consists of six laboratories: Optical Relay Mirror Laboratory, Fltsatcom Laboratory, Smart Structure Laboratory, Spacecraft Attitude Dynamics and Control Laboratory, Satellite Servicing Laboratory, and Spacecraft design Laboratory. The Fltsatcom Laboratory consists of a qualification model of the Navy communications satellite, FLTSATCOM, and associate ground support equipment for testing the satellite. The students under a spacecraft testing course send commands to a satellite for spinning the momentum wheel, firing thrusters etc and monitoring the telemetry. The students also get the opportunity to design and build small satellites. This curriculum is for 9 quarters. This curriculum is unique in several areas.

NPS Space Systems Operations curriculum emphasizes requirements and operations, as well as providing overview of science and technology/research and design. This curriculum provides a broader knowledge of space systems and it is for 8 quarters. The course matrix is shown in Fig. 3. This curriculum is related to information superiority (IS) curricula. It has 6 core courses of IS, Information Operations, Space Technology and Applications, Introduction to C4I, Information Assurance, Computer Network, and Modeling.

III. SPACECRAFT DESIGN PROGRAM

The major emphasis on spacecraft design is in Space Systems Engineering curriculum, where there are 17 core courses covering all spacecraft subsystems and payloads, as shown in Fig. 4, and three course sequence in spacecraft design. The spacecraft design sequence is AE 3870 Spacecraft Design Tools, AE 4870 Spacecraft Design I, and AE 4871 Spacecraft Design II. The Spacecraft Design Laboratory used for these is shown in Fig.5. It has taken about 15 years to develop the spacecraft design program.

In AE 3870, students become familiar with the spacecraft design tools which they use extensively in AE 4871. The tools include commonly used engineering software, such as Solid Works for CAD; NASTRAN and IDEAS for structural and thermal analyses; STK for orbit analyses; and Matlab/Simulink for spacecraft attitude control design. The tools also include specialized tools such as Aerospace Corporation Conceptual Design Center (CDC) software for preliminary spacecraft design trade-offs. This software is Excel based and has simple formulas for the design of orbits, space power, spacecraft attitude control, structures, and thermal subsystems.. It also has a database for spacecraft components so these components could be selected based on performance requirements. It provides accurate estimation of spacecraft mass. The design team for using the CDC software consists of a system engineer and sub-system engineers. The system engineer provides the overall performance requirements and coordinates the input from all sub-system engineers. This software is used extensively at Aerospace Corporation for feasibility study of future DoD space programs. There are several tools for spacecraft cost estimation in the laboratory. Because of the cost overrun of several DoD programs, accurate spacecraft cost estimation has become a critical area of expertise for space system engineers. The laboratory also has several software on communications system design.

The second course in the sequence is AE 4870 Spacecraft Design I. Before this course, students would have taken at least one course in each sub-system. However, they have generally not learned sub-system design for given requirements, systems engineering and system integration. In this course, the students learn design of subsystems, spacecraft design process, design trade-offs and do an individual design project for a GEO spacecraft for given performance requirements. Under this course, the students also finalize the performance requirements with the sponsor for the team spacecraft project for AE 4871.

The third course in the design sequence is AE 4871, Spacecraft Design II. In this course, the students do a team spacecraft design project. The performance requirements for the spacecraft are provided by the sponsor. The sponsor and mentors from space industry and Aerospace Corporation work closely with the students during the spacecraft design trade-offs and configuration selection. Table 1 gives a list of the projects undertaken in this course in the last ten years. Some of the projects have classified payloads. Students have clearances to do classified projects. Generally there are 10 to 15 students in a team. The students select their Program Manager as a team leader of the project and a System Engineer as technical leader for systems engineering. The Program Engineer and System Engineer assign responsibilities for

sub-system engineering to other students, including cost and test. Generally, each student has the primary responsibility for a sub-system and a secondary responsibility for the other sub-system. The instructor approves the team. This is a one quarter course and consists of a final review and a design report. In the first two weeks, performance requirements are finalized and approved by the sponsor and the instructor. In the next four weeks, spacecraft design trade-offs are performed and a spacecraft configuration and spacecraft components are selected for approval by the sponsor at the mid-term review. In the final four weeks, detailed analyses on spacecraft sub-systems are performed, final review of the project is held with external reviewers, and a spacecraft design report is written. In the final review, external reviewers from DoD organizations, space industry and Aerospace Corporation provide feedback to the students on the spacecraft design. The design project is selected based on primarily three considerations. First, the project is DoD relevance and is under consideration for future space programs. Second, the performance requirements are well defined by the sponsor. Third, the sponsor has adequate interest and resources to support the students. The course is very challenging as lot of work is performed in a quarter. It is equivalent to writing a proposal by space industry in 2.5 months in response to a request for proposal (RFP). The students are expected to provide enough depth in terms of analyses and hardware so that the sponsor feels comfortable with the design.

Some of the students get additional spacecraft design experience by designing, developing, testing, and operating small satellites as shown in Fig. 6 as part of their thesis work. The first NPS satellite, PANSAT, was launched aboard STS-95 in October 1998. It was a good experience for NPS students, faculty, and staff in space system design. It was a simple tumbling spacecraft with amateur radio digital communications. NPSAT 1 is under development and it is manifested on STP-1 Delta IV EELV in March 2006. It has two NRL experiments and four NPS experiments.

IV SPACECRAFT DESIGN PROJECT: Space Based Radar

As an example, this section provides a summary of a spacecraft design project, Ref. 2, Space Based Radar, under AE 4871 in 2002. The sponsors for the project were National Reconnaissance Office (NRO) and Air Force Research Laboratory (AFRL). This program is under active consideration by DoD for development. Low Earth Orbit (LEO) Space Based Radar project was undertaken in 1998. In 2002, it was decided to focus on Medium Earth Orbit (MEO). The mission of the spacecraft is imaging in synthetic aperture radar mode (SAR) and ground moving target indicator (GMTI). The specifications included SAR field of area, electronic scan area, GMTI minimum detectable velocity, geolocation accuracy, and detection probability.

Table 2 provides a list of mentors from different organizations. As it is clear from the list, the project is heavily supported by space industry. Table 3 gives a list of eleven team members and in brackets against their names the organizations they joined after graduation and the areas of their responsibility. The students provide a weekly progress report in all areas to the instructor. The instructor acts like a coach/mentor and provides resources. The students make the final decision on the design based on input from the instructor, sponsors, and space industry mentors. Table 4 provides the schedule of the project. It is very intense for 10 weeks and includes a mid-term review, final review, and a spacecraft design project. Table 5 gives the

overall requirements for the project. The requirements are 8 years design life, technology freeze date 2007, and first launch in 2012. The orbit is circular MEO with 10,000 km altitude, dual coverage between +/- 70 degree latitude and propellant for orbit raising of 300 km. The payload for the spacecraft is designed with 8.5 m x 55 m reflector, 0.3 m x 50 m phased array and 8 m focal length. The peak payload power is 5 kW and 200 minutes operations in orbit.

As shown in Fig. 7, two reflector configurations were evaluated for reflector structures. In the large circular reflector, only part of the reflector area is used for a signal reflection. It was simple to build and deploy, but its mass was too high and therefore was not selected. Figure 8 shows the selected deployed configuration. It is a three-axis-stabilized spacecraft with control moment gyros (CMGs) as actuators. Because of the large inertia of the spacecraft, CMGs are necessary to provide fast slew maneuvers. It is a 12 satellite constellation. The reflector and the phased array structures are designed for high stiffness and low thermal distortion and low thermal gradient. The two-axis solar array drive is used to keep the solar array normal to the sun's rays. Lithium Ion batteries are used for power storage. S-band is used for TT&C, V-band for X-link antennas and Ku-band D-link. Because of large X-link and D-link data, large on-board processing capacity is required. The feed array temperature gradient has to be kept in a very narrow range because of dimensional stability requirements. Table 6 gives the spacecraft mass budget. The estimated mass is based on the selection and use of actual equipment masses. The technology drivers for the spacecraft are payload, structures, and on-board processing. The power budget is shown in Table 7 for six modes: transfer orbit, deployment, standby, safe, slew, and payload operation. The power margin is approximately 20%.

The structure is designed for launch loads and natural frequency constraints of minimum 15 Hz axial, 10 Hz lateral during launch and 1.5 Hz on-orbit. The finite element model using IDEAS is shown in Figure 9. For the attitude dynamics and control systems, the performance requirements are: attitude knowledge of 0.0006 deg., pointing accuracy of 0.003 deg., and peak slew rate of 0.1 deg/sec. Table 8 shows the attitude dynamics and control subsystem (ADCS) components. It gives the selected components with numbers required in brackets, vendor, mass in Kg, and power in Watts. As shown in the table, the majority of the mass and power are required by CMGs. Figure 10 shows a Matlab/Simulink model for the analysis. Figure 11 shows the tracking pointing error from the simulation and it is within the allowable limits. Table 9 gives a list of external reviewers for the final review. It is clear that the reviewers consist of senior space experts from DoD, space industry, and Aerospace Corporation. The reviewers provide evaluation to the students on their design and suggest areas of improvements.

V. CONCLUSIONS

The objective of the space systems program at the Naval Postgraduate School (NPS) is to educate DoD space cadre personnel to fill each link in the National Security-Space Chain: requirements, science and technology/research and development, acquisition, and operation. The NPS space system program responds to sponsors' Educational Skill Requirements (ESR's). The major emphasis on spacecraft design is in Space Systems Engineering curriculum, where there are 17 core courses covering all spacecraft subsystems and payloads and a three course sequence in spacecraft design. Some students get additional spacecraft design experience by designing,

developing, testing, and operating small satellites as part of their thesis work. The spacecraft design program at the Naval Postgraduate School is unique in several areas.

VI REFERENCES

1. M. Rhoades, Space systems Curriculum Review, Naval Postgraduate School, November 2004.
2. Space Based Radar Design Project, Naval Postgraduate School, September 2002.

BRIJ N. AGRAWAL

Dr. Brij N. Agrawal is currently Distinguished Professor in the Department of Mechanical and Astronautical Engineering and Director of Spacecraft Research and Design Center at the Naval Postgraduate School. He has developed Spacecraft Design Program at the Naval Postgraduate School. Prior to joining NPS in 1989, he worked for twenty years for COMSAT and INTELSAT in satellite development. He wrote first book on spacecraft design, "Design of Geosynchronous Spacecraft" and published over 100 technical papers and a patent.

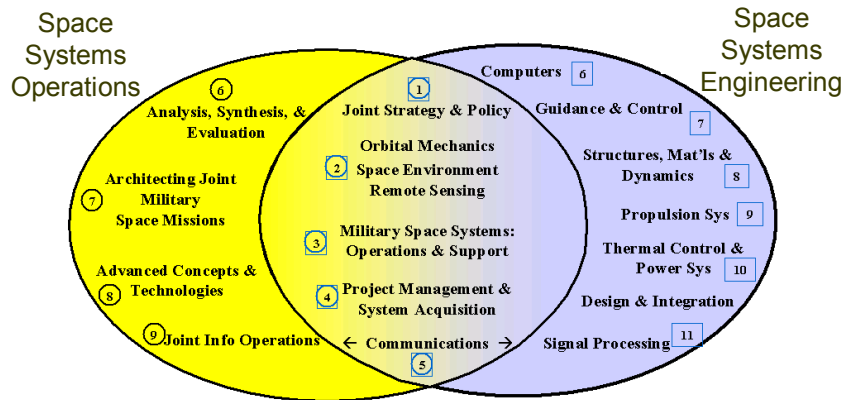


Figure 1. Educational Skill Requirements for Space Systems Curriculum

(591) Space Systems Engineering Restricted Line Officer Matrix FALL Entry (Eng Science Begins Jul 05) Updated: 29 OCT 2004					
Engineering Science Refresher Quarter - 400					
0 Su	Course MA2043 (2-0) Matrix Algebra	Course MA1115 (4-0) MA1116 (4-0) Multi-variable Calculus	Course PH1001 (4-2) & Mechanics	Course PH1002 (4-2) E&M	Course SS4000 (0-1) Seminar
Core Curriculum					
1 F	MA2121 (4-0) Differential Equations	AE2820 (3-2) Spacecraft Structures	EC2820 (3-2) Digital Logic Circuits	JPME - NW3230 (4-0) Strategy & Policy	SS4000 (0-1) Seminar
2 W	SS300 (4-2) Orbital Mech & Launch Sys	PH2514 (4-0) Space Environment	MA3046 (4-1) Matrix Analysis	EC2300 (3-2) Controls	SS4000 (0-1) Seminar
3 Sp	AE3815 (3-2) Spacecraft Dynamics	EO2525 (4-1) Analysis of Comm Signals	SS3525 (3-2) Remote Sensing	Degree Specialization	SS4000 (0-1) Seminar
4 Su	AE3851 (3-2) Spacecraft Propulsion	EO3525 (4-1) Communications Eng	AE3804 (3-0) Thermal Control of Spacecraft	Degree Specialization	SS4000 (0-1) Seminar
5 F	PH3360 (4-1) EM Waves (or PH2351 & 3352)	AE3818 (3-2) Spacecraft Attitude Dynamics & control	Degree Specialization	Degree Specialization	SS4000 (0-1) Seminar
6 W	AE3870 (2-2) (Accel) Spacecraft Design Tools	SS3051 (4-0) Space Control (Accel) TSS/CI	SS3001 (3-2) (Accel) Military Applications of Space TS/SCI	SS0810 (0-8) Thesis Research Experience Tour	SS4000 (0-1) Seminar
7 Sp	AE4870 (4-0) Spacecraft Design 1	EC3230 (3-1) Space Power	SS3035 (3-2) Microprocessors (or EC2840 & 3800)	Degree Specialization	SS4000 (0-1) Seminar
8 Su	AE4871 (2-4) Spacecraft Design 2	Degree Specialization	Degree Specialization	SS0810 (0-8) Thesis Research	SS4000 (0-1) Seminar
9 F	MN3331 (5-1) Systems Acq & PM	SS0810 (0-8) Thesis Research	SS0810 (0-8) Thesis Research	Degree Specialization	Preparatory Courses 591 Core Degree Specialization JPME

Figure 2 Space System Engineering Course Matrix

QUARTER	COURSE	COURSE	COURSE	COURSE	COURSE
0 (refresher-- 12 wks recom.)	MA1113 (4-0) Single Var Calc	MA1114 (4-0) Matrix Algebra	PH1001 (4-2) Mechanics	PH1002 (4-2) Electricity & Mag	
18					
1 (fall)	MO1903 (3-0) Applied Math for Space Sys	SS3011 (3-0) Space Tech/Appl	CC3000 (4-0) C4ISR IS Requirement USN	JPME - USN NW3230(4-2) Strat&Policy	SS4000 (0-1) Seminar
15.5					
2 (winter)	OS2100 (3-1) Probability/Stats	SS3500 (4-2) Orbital Mech & Launch Sys	IS3502 (3-2) Comp Networks & Appl IS Requirement USN	JPME - USN NW3285 (4-0) NSDM	SS4000 (0-1) Seminar
17					
3 (spring)	EO3516 (4-2) Intro Comm Sys Eng	PH12514 (4-0) Space Environment	AE4830 (3-2) S/C Systems 1	JPME - USN NW3275 (4-0) JMO Part 1	SS4000 (0-1) Seminar
17.5					
4 (summer)	EO4516 (4-2) Comm Sys Anal	MN3331 (5-1) ACQ Mgmt	CS3000 (4-1) Great Principles of Comp Tech IS Req - USN	JPME - USN NW3276 (2-2) JMO Part 2	SS4000 (0-1) Seminar
18.5					
5 (fall)	PH3052 (4-0) Remote Sensing	SS3041 (4-2) Space Sys & Ops 1	SS3613 (3-0) MILSATCOM Sys & Appl SECRET	AE 4831 (3-2) S/C Systems 2	SS4000 (0-1) Seminar
16.5					
6 (winter)	SS3051(4-0) Space Control (1st half QTR) TS/SCI	SS3001 (3-2) Mil Appl of Space (1st half QTR) TS/SCI	SS0810 (0-8) Thesis	Experience Tour (2nd half QTR)	SS4000 (0-1) Seminar
16.5					
7 (spring)	SS4051(3-2) Mil Space Sys/ Arch TS/SCI	SS0810 (0-8) Thesis	Elective	IW 3101 (4-1) Info Operations IS Requirement	SS4000 (0-1) Seminar
17					
8 (summer)	SS 0810 (0-8) Thesis	SS 0810 (0-8) Thesis	Elective	OS3307 (4-1) Modeling Practice IS Requirement USN	SS4000 (0-1) Seminar
16					

Legend	
Prep Courses	
366 Core	
N6 IS core - USN Only	
JPME	

Figure 3. Space Systems Operations Course Matrix

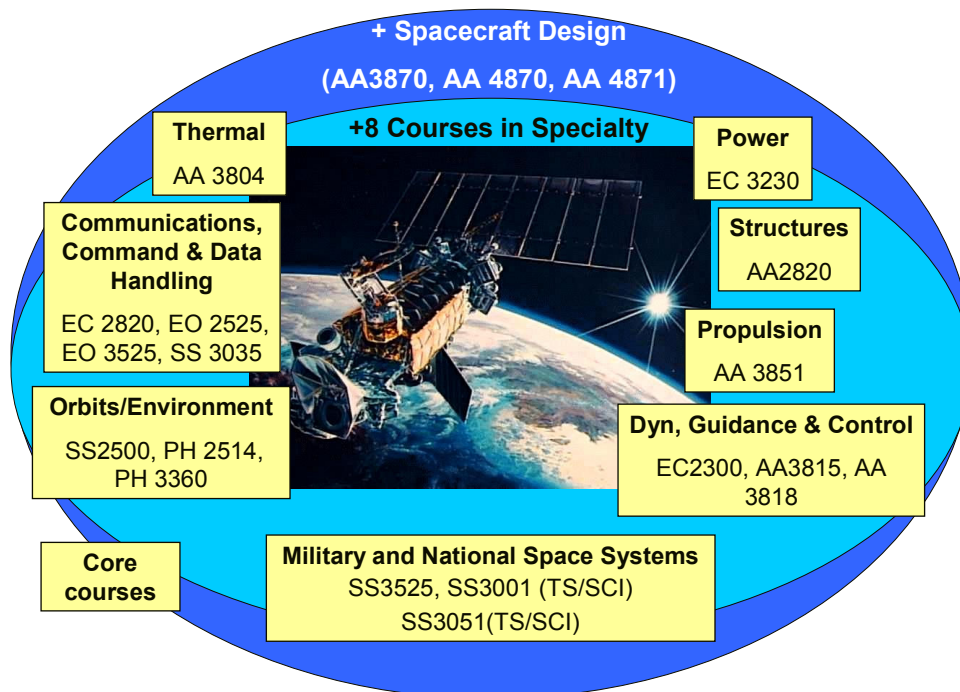
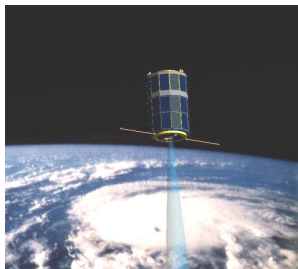


Figure 4. Spacecraft Design Programs



Figure 5 Spacecraft Design Laboratory

PANSAT launched aboard STS-95 (Oct. 1998)
Experience for NPS students, faculty and staff (build-test-fly)
50+ graduate theses
Amateur radio digital communications
Tumbling, 'simple' space vehicle



NPSAT1 - Manifested on STP-1 Delta IV EELV (Mar. 2006)
Hands-on education in Space Systems
Class D spacecraft
Demonstrating low-cost, small satellite technology
Platform for 2 NRL experiments + 4 NPS experiments

Figure 6. NPS Small Satellite Design Program

- **Advanced Polar Satellite - 2003**
- **Space Based Radar –2002 (Sponsor:AFRL/NRO)**
- **Guardian Spacecraft (EHF communications satellites in LEO with classified Payload-2001(Sponsor: NRO)**
- **Mithra Bifocal Relay Mirror Satellite-2000 (Sponsor: AFRL)**
- **NPSAT-1 , Multi-spectral Imagery-1999**
- **NPS Space Based Radar Spacecraft-1998 (Sponsor: NRO)**
- **MEO UHF Satellite Constellation for robust Assured Telecommunications- summer 1997 (Sponsor-Navy)**
- **EHF Satellite (classified payload)- summer1997 (Sponsor-NRO)**
- **Multiple Asteroid Explorer- Winter 1997 (Sponsor-AIAA)**
- **Spectral Sensing Space system-1996 (Sponsor-Air Force)**

Table 1. Spacecraft Design Projects

 <ul style="list-style-type: none"> •Mark Miller •Frank Kantrowitz •Chris Kobel •Edwin Berry •Ken Mercer •Elias Polendo •Bill Neel •David Gilmore •Bernie Yoo •David Kretzmann •Doug Daughaday •Rhoda Novak •Bill Fischer •Ron Hovden •Don Yang •Julie Heim •Joseph Aquilar •Don Nelson •Keith Coste 	 <ul style="list-style-type: none"> •Maj Chris Garrett •Bob Brooker •Dan Gallagher 	 <ul style="list-style-type: none"> •Peter Chase •David Rohweller  <ul style="list-style-type: none"> •Eric Larson 	 <ul style="list-style-type: none"> •Mason Peck •Jack Jacobs •Pietro Di Leonardo
 <ul style="list-style-type: none"> •Jennifer Mailly •Matt Currier 	 <ul style="list-style-type: none"> •Brian Smith •Ron Diamond  <ul style="list-style-type: none"> •Bernard Jackson 	 <ul style="list-style-type: none"> •Roger May 	 <ul style="list-style-type: none"> •Rob Atkinson •Tom Alexiou •Dan Barron
		 <ul style="list-style-type: none"> •Olwen Morgan •Marlene Huntsinger 	

Table 2. Mentors for the Space Based Radar Project

LCDR Bob Porter	Program Manager
LCDR Rob Stevens (NRO)	Systems Engineer
LT Gary Cave (SWOSC-Newport)	Spacecraft Structure
LT Mike Snelling (SPAWAR-San Diego)	Payload Design
LT Jeff King (NRO)	Astrodynamics
LT Steve Werner(SWOSC-Newport)	Launch Vehicle / Propulsion
LCDR Craig Coleman (NRO)	Telemetry, Tracking, & Command
Capt Tiina Olson (NRO)	Electric Power Subsystem
LT Scott Josselyn	Attitude Dynamics & Control
LCDR Ron Bishop (NRO)	Thermal Control
Capt Rick Luce (NRO)	Cost / Risk / Test

Table 3. Design Project Team for Spacecraft Design II

8 Jul	Beginning of the Quarter
15 Jul	Trip to Aerospace Corporation
22 Jul - 9 Aug	Subsystem Trade Studies
24 Jul	Trip to Astro Aerospace (TRW)
12 Aug	Mid-term Review
13 Aug- 9 Sep	Finalize Configuration / Analysis
9 - 17 Sep	Prepare for Final Review
18 Sep	Final Review

Table 4. Spacecraft Design Project Schedule

General

- 8-year design life
- Technology freeze date: 2007
- First launch: 2012

Orbit

- MEO (10,000 km)
- Dual coverage between $\pm 70^\circ$ latitude
- Raise orbit 300 km at EOL

Payload

- 8.5 m x 55 m reflector (1200 kg)
- 0.3 m x 50 m phased array (180 kg)
- 8 m focal length

Power

- 5 kW peak payload power
- 200 min operation per orbit

Table 5. Mission Requirements

Structure/structural deployment are design drivers

Two feasible reflector structure concepts:

- Cylindrical structure
- Boom structure

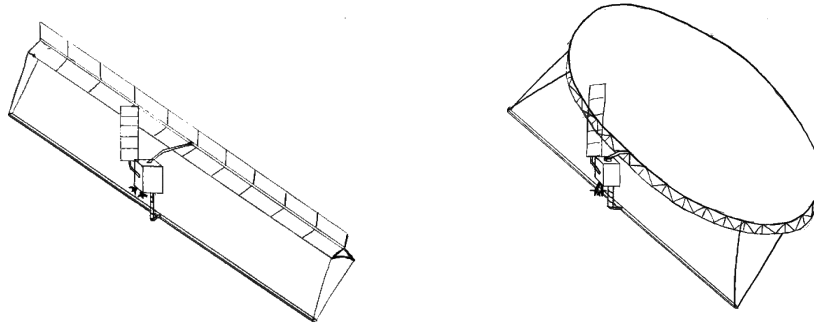


Figure 7. Configuration Trade Studies

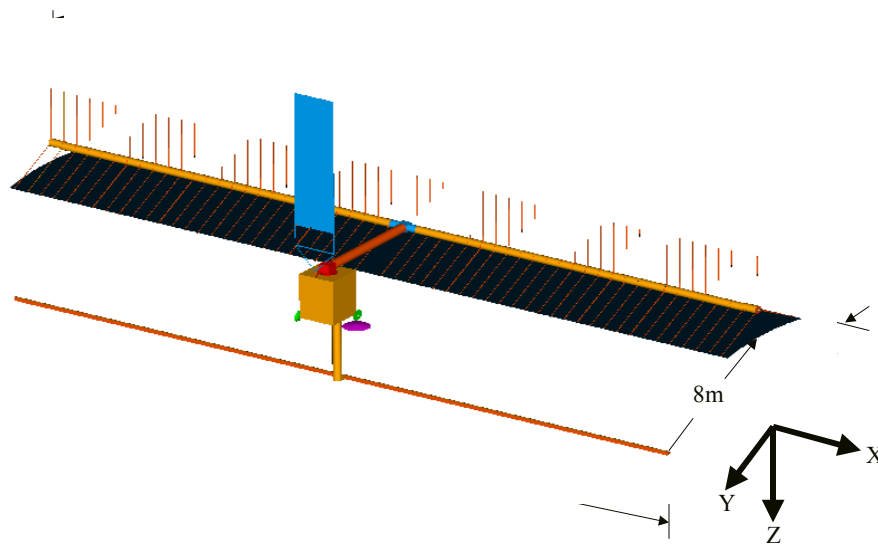


Figure 8. Deployed Configuration

Subsystem	Mass [kg]
Structure	935
SCE	45
Payload	1450
Processing	465
TTC	250
Thermal	415
Power	440
ADCS	290
Propulsion	270
Mech Integration	70
Elect Integration	190
TOTAL launch*	5540
TOTAL Dry	5150

* Includes adapter and 15% margin

Table 6. Spacecraft Mass Budget

Operating modes	SCE	Payload	Processing	ADCS	Thermal(Eclipse)	Thermal (Non-eclipse)	Power(Non-eclipse)	Propulsion	TT&C	Structures	Total (Eclipse)	Total(Non-eclipse)	weighted avg margin (E)	adjusted total eclipse	weighted avg margin (NE)	adjusted total non-eclipse
Transfer Orbit	135			46		300	30	15			226	526	0.19337	270	0.22565	645
Deployment	135			522	2839	300		15	70		3581	1042	0.24508	4459	0.2331	1285
Standby	135	500	575	316	2282	230	60	50	182		4040	2048	0.22374	4944	0.19673	2451
Safe	135			427	2839	300	60		15		3416	937	0.24111	4240	0.21441	1138
Slew	135	500	575	532	1507	300	60		285		3534	2387	0.21326	4288	0.19435	2851
Payload Op.	135	4230	1800	318	100	100	60	0	285	0	6868	6928	0.20	8218	0.20	8290
Power Margin*	0.2	0.2	0.2	0.2	0.25	0.25	0.2	0.2	0.1	0.5						

Table 7. Spacecraft Power Budget

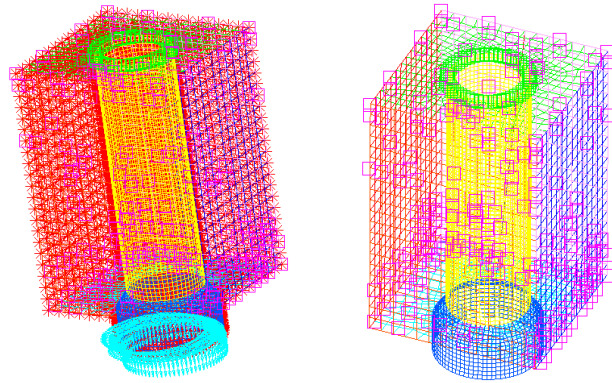


Figure 9. Finite Element Model

Component	Vendor	Mass (kg)	Power (W)
Sun sensor (4)	Adcole	1.0	0.5
Earth sensor (1)	Barnes	2.6	10
Star tracker & electronics (3)	Ball	16	20.0
Gyros (2x3)	Litton	1.3	20.0
CMGs (4)	Honeywell	256	260.0
GPS receiver (2)	Motorola	2.6	4.8
Interface electronics		1.0	1.0
ADACS computers	IBM	10	10.0
S subsystem total		289 kg	326 W

Table 8. ADCS Components

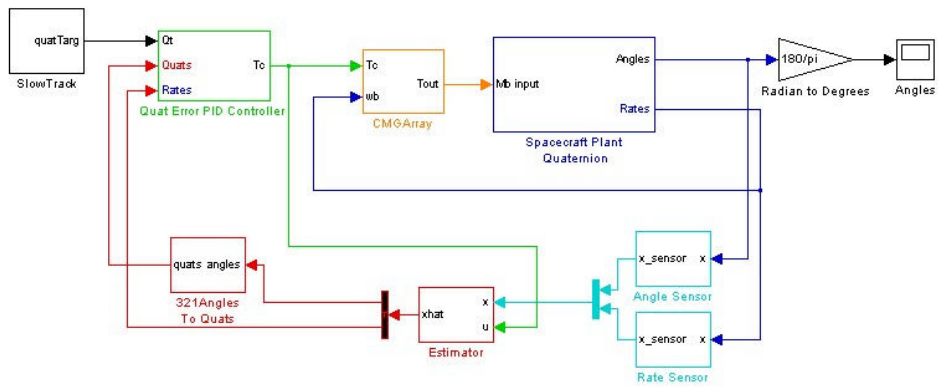


Figure 10. Simulink Model

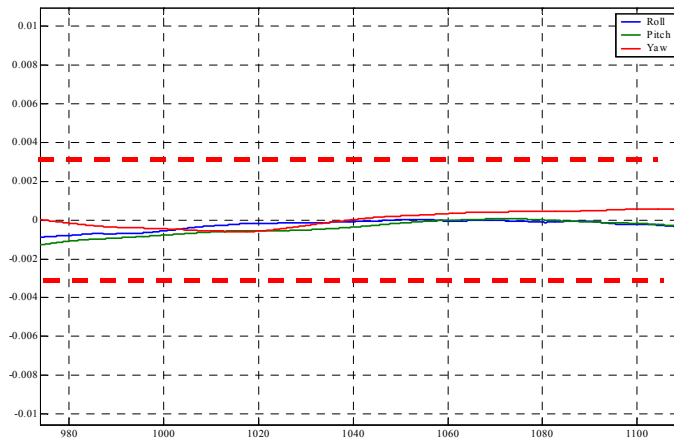


Figure 11. Tracking Pointing Error

Maj. General Robert Dickman (Retd.) , Air Force
Ms. Tracy Malone (NRO)
Mr. Will Troxell (NRO)
Mr. Bernard Collins (NRO)
CAPT. Al Scott (NRO)
LCDR Mike Rayfield (NRO)
LCDR Kurt Allred (NRO)
Dr. Joe Straus (Aerospace)
Mr. Bill Hiatt (Aerospace)
Mr. Mark Miller (Aerospace)
Mr. Joseph Aguilar (Aerospace)
Mr. Frank Schawan (Lockheed Martin)
Mr. Rand Hyden (Lockheed Martin)
Mr. Abbas Salim (Lockheed Martin)
Dr. Mason Peck (Honeywell)
Mr. David Rohweller (TRW)
Mr. Eric G. Butte (Loral)

Table 9. Reviewers for Final Review